Role of Large Gluonic Excitation Energy for Narrow Width of Penta-Quark Baryons in QCD String Theory

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We study the narrow decay width of low-lying penta-quark baryons in the QCD string theory in terms of gluonic excitations. In the QCD string theory, the penta-quark baryon decays via a gluonic-excited state of a baryon and meson system, where a pair of Y-shaped junction and anti-junction is created. Since lattice QCD shows that the lowest gluonic-excitation energy takes a large value of about 1 GeV, the decay of the penta-quark baryon near the threshold is considered as a quantum tunneling process via a highly-excited state (a gluonic-excited state) in the QCD string theory. This mechanism strongly suppresses the decay and leads to an extremely narrow decay width of the penta-quark system.

1. 3Q, 4Q, 5Q Potentials and Color-Flux-Tube Picture from Lattice QCD

In 1969, Nambu first presented the string picture for hadrons [1]. Since then, the string theory has provided many interesting ideas in the wide region of the particle physics.

Recently, various candidates of multi-quark hadrons (penta-quarks and tetra-quarks) have been experimentally observed [2]. As a remarkable feature of multi-quark hadrons, their decay widths are extremely narrow [3], which gives an interesting puzzle in the hadron physics. In this paper, we study the narrow decay width of penta-quark baryons in the QCD string theory [4,5], with referring recent lattice QCD results [5,6,7,8,9,10,11,12].

First, we show the recent lattice QCD studies of the inter-quark potentials in 3Q, 4Q and 5Q systems [5,6,7,8,9], and revisit the color-flux-tube picture for hadrons. For more than 300 different patterns of spatially-fixed 3Q systems, we perform accurate and detailed calculations for the 3Q potential in SU(3) lattice QCD with (β=5.7, $12^3 \times 24$), (β=5.8, $16^3 \times 32$), (β=6.0, $16^3 \times 32$) and ($\beta = 6.2$, 24^4), and find that the ground-state 3Q potential $V_{\rm 3Q}^{\rm g.s.}$ is well described by the Coulomb plus Y-type linear potential, i.e., Y-Ansatz,

$$V_{\rm 3Q}^{\rm g.s.} = -A_{\rm 3Q}\sum_{i<j}\frac{1}{|\mathbf{r}_i-\mathbf{r}_j|}+\sigma_{\rm 3Q}L_{\rm min}+C_{\rm 3Q}, \tag{1}$$

within 1%-level deviation [5,6,7]. Here, $L_{\rm min}$ is the minimal value of the total length of the flux-tube, which is Y-shaped for the 3Q system. To demonstrate this, we show in Fig.1(a) the 3Q confinement potential $V_{\rm 3Q}^{\rm conf}$, i.e., the 3Q potential subtracted by the

Coulomb part, plotted against the Y-shaped flux-tube length $L_{\rm min}$. For each β, clear linear correspondence is found between the 3Q confinement potential $V_{\rm 3Q}^{\rm conf}$ and $L_{\rm min}$, which indicates Y-Ansatz for the 3Q potential.

Furthermore, a clear Y-type flux-tube formation is actually observed for the spatially-fixed 3Q system in lattice QCD [5,12]. Thus, together with recent several other analytical and numerical studies [13,14,15], Y-Ansatz for the static 3Q potential seems to be almost settled. This result indicates the color-flux-tube picture for baryons.

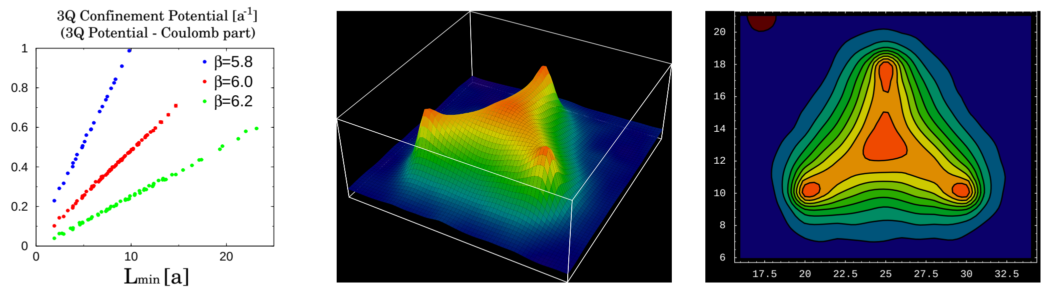

Figure 1. (a) The 3Q confinement potential $V_{\rm 3Q}^{\rm conf}$, i.e., the 3Q potential subtracted by the Coulomb part, plotted against the Y-shaped flux-tube length $L_{\rm min}$ in the lattice unit. (b) The lattice QCD result for Y-type flux-tube formation in the spatially-fixed 3Q system.

We perform also the first study of the multi-quark potentials in SU(3) lattice QCD [5,8,9], and find that they can be expressed as the sum of OGE Coulomb potentials and the linear potential based on the flux-tube picture. (This lattice result presents the proper Hamiltonian for the quark-model calculation of the multi-quark systems.) In fact, the lattice QCD study indicates the color-flux-tube picture even for the multi-quark systems.

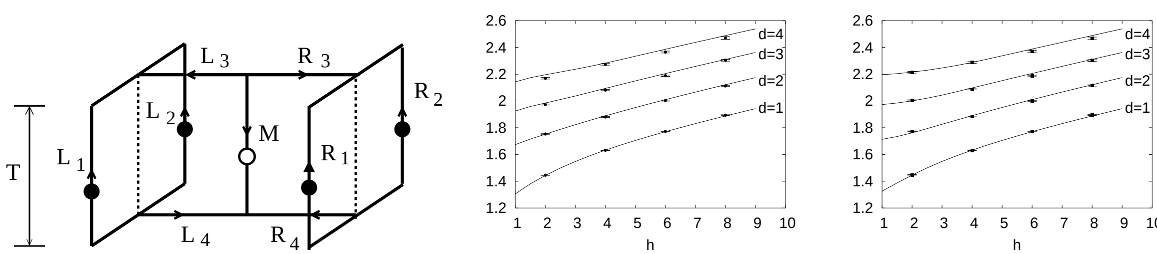

Figure 2. (a) The penta-quark (5Q) Wilson loop $W_{\rm 5Q}$ for the calculation of the 5Q potential $V_{\rm 5Q}$. (b) $V_{\rm 5Q}$ for planar configurations and (c) $V_{\rm 5Q}$ for twisted configurations. The symbols denote the lattice QCD results, and the curves the OGE plus multi-Y Ansatz.

2. The Gluonic Excitation in the 3Q System

Next, we study the gluonic excitation in lattice QCD [5,10,11]. In the hadron physics, the gluonic excitation is one of the interesting phenomena beyond the quark model, and relates to the hybrid hadrons such as $q\bar{q}G$ and $qqqG$ in the valence picture [16].

For about 100 different patterns of 3Q systems, we perform the first study of the excited-state potential $V_{\rm 3Q}^{\rm e.s.}$ in SU(3) lattice QCD with $16^3\times 32$ at β=5.8 and 6.0 by diagonalizing the QCD Hamiltonian in the presence of three quarks. The gluonic-excitation energy

$\Delta E_{3Q} \equiv V_{3Q}^{e.s.} - V_{3Q}^{g.s.}$ is found to be about 1GeV in the hadronic scale [5,10,11]. This result indicates that the lowest hybrid baryon $qqqG$ has a large mass of about 2 GeV. [1]

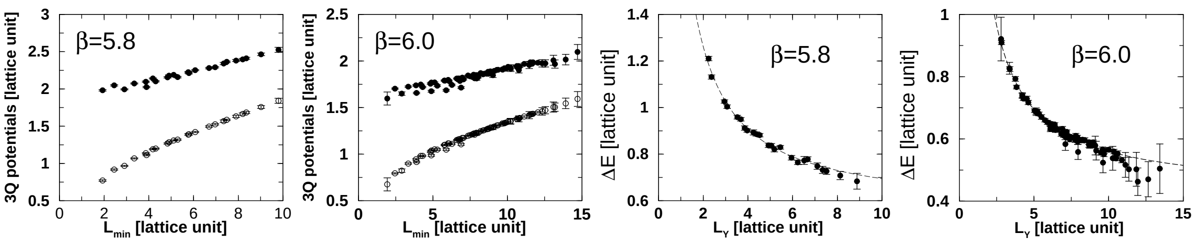

Figure 3. (a) & (b) The 1st excited-state 3Q potential $V_{3Q}^{e.s.}$ and the ground-state 3Q potential $V_{3Q}^{g.s.}$. (c) & (d) The gluonic excitation energy $\Delta E_{3Q} \equiv V_{3Q}^{e.s.} - V_{3Q}^{g.s.}$. The dashed curve denotes the "inverse Mercedes Ansatz" [5,11].

3. The QCD String Theory for the Penta-Quark Decay

Our lattice QCD studies on the various inter-quark potentials indicate the flux-tube picture for hadrons, which is idealized as the QCD string model. Here, we consider penta-quark dynamics, especially for its extremely narrow width, in the QCD string theory.

The ordinary string theory mainly describes open and closed strings corresponding to $Q\bar{Q}$ mesons and glueballs, and has only two types of the reaction process: the string breaking (or fusion) process and the string recombination process.

On the other hand, the QCD string theory describes also baryons and anti-baryons as the Y-shaped flux-tube, which is different from the ordinary string theory. Note that the appearance of the Y-type junction is peculiar to the QCD string theory with the SU(3) color structure. Accordingly, the QCD string theory includes the third reaction process: the junction (J) and anti-junction ($\bar{\mathrm{J}}$) par creation (or annihilation) process. (Through this J-$\bar{\mathrm{J}}$ pair creation process, the baryon and anti-baryon pair creation can be described.)

Figure 4. The junction (J) and anti-junction ($\bar{\mathrm{J}}$) par creation (or annihilation) process.

As a remarkable fact in the QCD string theory, the decay/creation process of penta-quark baryons inevitably accompanies the J-$\bar{\mathrm{J}}$ creation [4,5] as shown in Fig.5. Here, the intermediate state is considered as a gluonic-excited state, since it clearly corresponds to a non-quark-origin excitation [5].

The lattice QCD study indicates that such a gluonic-excited state is a highly-excited state with the excitation energy above 1GeV. Then, in the QCD string theory, the decay process of the penta-quark baryon near the threshold can be regarded as a quantum

[1]Note that the gluonic-excitation energy of about 1GeV is rather large compared with the excitation energies of the quark origin. Therefore, for low-lying hadrons, the contribution of gluonic excitations is considered to be negligible, and the dominant contribution is brought by quark dynamics such as the spin-orbit interaction, which results in the quark model without gluonic modes [5,10,11].

tunneling, and therefore the penta-quark decay is expected to be strongly suppressed. This leads to a very small decay width of penta-quark baryons.

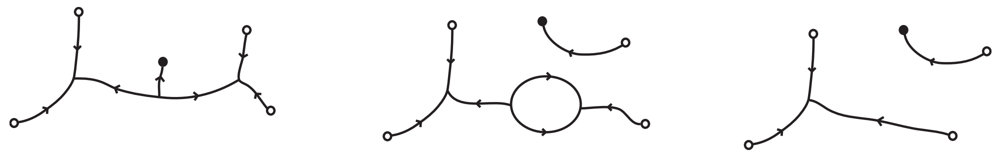

Figure 5. A decay process of the penta-quark baryon in the QCD string theory. The penta-quark decay process inevitably accompanies the J-$\bar{\mathrm{J}}$ creation, which is a kind of the gluonic excitation. There is also a decay process via the gluonic-excited meson.

Now, we estimate the decay width of penta-quark baryons near the threshold in the QCD string theory. In the quantum tunneling as shown in Fig.5, the barrier height can be estimated as the gluonic-excitation energy $\Delta E \simeq 1\mathrm{GeV}$ of the intermediate state. The time scale T for the tunneling process is expected to be the hadronic scale as $T = 0.5 \sim 1\mathrm{fm}$, since T cannot be smaller than the spatial size of the reaction area due to the causality. Then, the suppression factor for the penta-quark decay can be roughly estimated as $|\exp(-\Delta ET)|^2 \simeq |e^{-1\mathrm{GeV}\times(0.5\sim 1)\mathrm{fm}}|^2 \simeq 10^{-2} \sim 10^{-4}$. Note that this suppression factor $|\exp(-\Delta ET)|^2$ appears in the decay process of low-lying penta-quarks for both positive- and negative-parity states. For the decay of $\Theta^+(1540)$ into N and K, the decay width would be controlled by the Q-value, $Q \simeq 100\mathrm{MeV}$. Considering the extra suppression factor of $|\exp(-\Delta ET)|^2$, we get a rough order estimate for the decay width of $\Theta^+(1540)$ as $\Gamma[\Theta^+(1540)] \simeq Q \times |\exp(-\Delta ET)|^2 \simeq 1 \sim 10^{-2}\mathrm{MeV}$.

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